MODELING ODOR DISPERSION FROM MULTIPLE SOURCES TO MULTIPLE RECEPTORS

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ABSTRACT

A model to predict the influence of odor dispersion from multiple sources to multiple receptors was developed. The intention of this model was to provide a tool for evaluating the odor load changes to a community when siting new swine production systems or during expansion of existing swine production systems. The model can also be used to predict the odor load for existing production systems and how a change in odor control technologies will impact the odor load in the community. The model developed can handle up to 20 swine production sources with up to 100 receptors in a community of any size. The model incorporates historical average local weather data, coordinate locations of all sources and receptors, source production arrangement, and any odor reducing technologies incorporated. The model predicts the number of hours of exposure to odors of varying strength from which decisions can be made on whether or not a proposed siting decision is prudent, or, the odor control technologies that would result in an acceptable odor load to the community.

Keywords: Odor, modeling, plume

INTRODUCTION

Current siting requirements for new livestock and poultry production systems in the US are based mainly on animal units and distance to the nearest neighbor. This strategy has resulted in negative impacts to the swine industry. Separation distance alone does not account for existing odor sources in a community, nor the influence of localized weather patterns on odor transmission. A better approach would be to provide for the industry and community residents a procedure for making prudent decisions on where a facility of a given size could be placed in a community with an existing odor load. In this manner decisions could be made on not only separation distance, but also as it relates to historical weather patterns, size of production facility, odor control measures implemented, and existing odor loads in a community.

Most all models associated with gas dispersion use some form of the Gaussian Plume model (Turner, 1994). Although arguments for and against this modeling procedure have persisted over time, it was felt that this approach would provide a fair and consistent procedure that could be applied to many different production strategies. There was no attempt with the model developed to try and predict all of the complicating features present in most all odor dispersion situations. Instead, it was decided that a standard form of the Gaussian Plume model would be implemented, with a standard set of parameters and procedures applied to various swine production practices. For various production systems, calibration data collected would then allow for calibration factors to be

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included in an attempt to describe on average the historical effects of odor dispersion in a community. In other words, the concern of the model developed here was not to be able to describe odor transmission on an hour-by-hour, day-by-day, etc. basis. Instead, historical average conditions, along with parameters that reasonably describe odor sources, were implemented in an attempt to provide a siting tool that predicts historical average expectations. When a facility is built in a community, it is felt that the long-term implications are more important than the day-to-day implications of having a production facility in a community.

MODELING ODOR DISPERSION

The approach used for this model incorporated the basic Gaussian Plume model for predicting the maximum ground-level centerline concentration as given in Equation 1:

(1)

$$C = \frac{Q}{us_Z s_y p} e^{-H_e^2/2s_Z^2}$$

where;

C	=	concentration of emitted substance at a receptor, g/m^3
Q	=	source emission rate of substance, g/s
u	=	horizontal wind velocity, m/s
He	=	source emission height above the ground, m
s_z	=	vertical standard deviation of the plume, m
s_y	=	horizontal standard deviation of the plume, m

The vertical and horizontal standard deviations of the plume are further defined to be:

(2)

$$s = e^{\{I + J(\ln x) + K(\ln x)^2\}}$$

where;

x	=	downwind distance from source, km
s	=	rural dispersion coefficient, m

The coefficients I, J, and K are based on Pasquill's atmospheric stability class (McMullen, 1975). Table 1 defines the coefficients used.

There is a problem in using Equation 1 directly for determining downwind odor strength. An actual source emission rate (g/s) is not a possible measurement from which to base predictions of odor concentration in g/m^3. For predicting downwind odor strength, a knowledge of the source emission rate of odors (OU/s for example), and the volumetric flow rate of the plume at any given downwind distance would yield an estimate of downwind odor strength. Within Equation 1, the term:

(3)

$$\frac{us_Z s_y p}{e^{-H_e^2/2s_Z^2}}$$

was used to predict the downwind volumetric flow rate of the plume (m^3/s). This prediction is very useful for determining downwind odor levels as it relates directly to the currently recommended methods for measuring odor strength (i.e. olfactometry). If one knows the strength of odor leaving a source, and the volumetric flow rate associated with that source, then knowing the volumetric flow rate of the plume at any given downwind distance will allow for a prediction of the average odor strength within the plume.

Table 1. Vertical (s_z) and horizontal (s_y) standard deviation coefficients.

Pasquill Stability	s_z coefficients			s_y coefficients		
Class	I	J	K	I	J	K
A	6.035	2.1097	0.2770	5.357	0.8828	-0.0076
B	4.694	1.0629	0.0136	5.058	0.9024	-0.0096
C	4.110	0.9201	-0.0020	4.651	0.9181	-0.0076
D	3.414	0.7371	-0.0316	4.230	0.9222	-0.0087
E	3.057	0.6794	-0.0450	3.922	0.9222	-0.0064
F	2.621	0.6564	-0.0540	3.533	0.9191	-0.0070

Source Odor Loads

Two basic source conditions are included in the model. Source odor loads associated with building ventilation air and source odor loads associated with outdoor storage systems are included. Each is described below.

Building Ventilation Air

Odor emission from buildings is a function of ventilation rate and the associated odor strength. Ventilation rate is in turn a function of outside climate, desired inside temperature, animal maturity level, and animal density. No distinction is made in the model for natural versus mechanically ventilated structures. The reasoning being is that if a building is being ventilated for temperature and or moisture control, at levels recommended for raising animals, then on average the building air exchange rate for both systems will be nearly the same. More importantly however are the seasonal changes in ventilation rate required to maintain desired interior climates for raising animals. The basic strategy followed in the model is as follows:

1. Determine average weight of animals in building (W)
2. Determine average seasonal temperature (T) for the period of time under consideration
3. Determine average ventilation rate required per animal (VPA)
4. Calculate average required whole-building ventilation rate (VB)

Table 2 outlines the specific procedure followed. In general, recommended minimum and maximum design ventilation rates (MWPS, 1990) were used. For ambient temperatures below -1 C (30 F), the minimum ventilation rate was used. For ambient temperatures above 21 C (70 F), the maximum ventilation rate was used. Between -1 and 21 C ambient temperatures, the ventilation rate was estimated with the relations shown in Table 2.

Table 2. Building ventilation rate determination as a function of average outdoor temperature.

Pig Maturity Class	VPA (m^3/hr-animal)	Valid T (C)	Min VPA	Max VPA
Nursery	VPA=3.4 + (T+1)*(39.1/22)	-1 to 21	3.4	42.5
Finishing	VPA=11.9 + (T+1)*(115.6/22)	-1 to 21	11.9	127.5
Sows/Litters	VPA=25.5 + (T+1)*(229.5/22)	-1 to 21	25.5	255.0

Outdoor Storage Systems

Outdoor storage systems were categorized into two classes. Near ground-level sources such as lagoons and earthen basins and above-ground sources such as slurry-store systems. For ground-level sources, a procedure utilizing storage boundary measurements (i.e. Aberm@) and theoretical boundary-layer thicknesses at the berm were utilized. The volumetric flow rate leaving a ground-level source was estimated by determining the flow net leaving a source. To accomplish this task, an equivalent diameter for all ground-level sources was determined:

$$D_{eq} = \left(\frac{4A_{storage}}{p} \right)^{0.50} \tag{4}$$

This equivalent diameter was used to predict the downwind path length that formed the boundary-layer thickness downwind at the berm. At a downwind berm distance of D_{eq}, the boundary-layer height, assumed turbulent, was determined from the following relationship (Holman, 1997):

$$H_{BL} = \frac{D_{eq}^{\ 0.80}(0.042)}{WS^{0.20}} \tag{5}$$

The theoretical turbulent boundary layer velocity profile was used (Holman, 1997):

$$U(y) = WS\left(\frac{y}{H_{BL}} \right)^{1/7} \tag{6}$$

Integrating the theoretical velocity profile between the ground and H_{BL}, multiplied by the transverse width of the source (D_{eq}) results in the theoretical volumetric flow rate used in the model for ground-level sources:

$$V_{storage} = 0.875 D_{eq} WS \left(H_{BL} \right) \tag{7}$$

where;

D_{eq}	= Equivalent diameter of storage system, m
$A_{storage}$	= Actual surface area of storage system, m^2
H_{BL}	= Boundary-layer height at the berm, downwind from storage system, m
WS	= Free-stream (10 m height) wind speed, m/s
U(y)	= Air velocity within boundary-layer, m/s
$V_{storage}$	= Volumetric flow rate of odorous air leaving a source, m^3/s
y	= height above area source, m

Source Odor Loads

The building and storage system source odor loads were determined by multiplying the estimated source ventilation rates ($V_{Building}$ or $V_{Storage}$) by the estimated source odor strength ($OU_{Building}$ or $OU_{Storage}$). Source odor strengths used in the model are given in Table 3.

Table 3. Source odor strengths used in model.

Source	**Building or Storage Odor Strength, OU (m^3 fresh-air/m^3 odorous air)**	**Min**	**Max**
Deep-pit building	500 + (21-T)*(500/22)	500	1,000
Building flushed with uncovered lagoon effluent	300 + (21-T)*(300/22)	300	600
Building flushed with covered lagoon effluent	760		
Pull-plug	760		
Uncovered lagoon (non-purple), berm	382		
Covered lagoon, berm	164		
Earthen basin, berm	910		
Above ground storage, berm	910		

In all model calculations, the overall size of the production source is estimated from known dimensions of the manure storage and building system. From this overall site footprint, an equivalent diameter for the entire site is determined. This equivalent diameter is in turn used in the model to determine exposure angles between an odor source and a receptor. This information is then used to determine the percentage of time (historically) that a receptor would be in the downwind plume of a source.

Model Capabilities

The parameters presented were used to predict odor strength levels downwind from multiple sources to multiple receptors. Currently, the model can handle up to 20 sources and 100 receptors in a land base of any size. The model is intended as a tool to help site new facilities and to evaluate the effectiveness of odor control technologies for both new and existing facilities. The model considers the overall size of a pig production system, the type of pig production system, local historical weather conditions, and odor control implementation. The model predicts the number of hours of exposure to various levels of odor, by month, for a given community. An example will be used to demonstrate the model's capability.

Example Source Calculations

Suppose the following scenario exists. A deep-pit swine production system consisting of 4,000 finishing pigs exists in Omaha, Nebraska (USA). Surrounding this production facility are eight neighbors, located at the four diagonal compass points either 400 m (0.25 miles) or 800 m (0.50 miles) away (NE, SE, SW, NW). What are the predicted number of hours between March and October that each neighbor would experience odors at a strength of OU=7 or greater for an historical average year? Table 4 outlines the calculations used in the model for the source odor load by month. The predicted number of hours between March and October that a neighbor would be subjected to odors of a strength OU=7 or greater is summarized in Table 5.

The modeled results given in Table 5 were calculated by using historical average monthly wind speed and solar information to predict daytime dispersion characteristics. During nighttime conditions, the model assumes one-half the night at a class D stability and the remaining nighttime at a class E stability, with nighttime hours varied by season of the year. To fully utilize the results from the model, a criteria would need to be established for the maximum percent time of exposure to various odor strengths. Clearly though, Table 5 outlines two critical features of siting; separation distance and location relative to predominant winds play a major role in exposure times to odors. Receptors 2 and 4, located along the NW-SE diagonal at a distance of 400 m from the source experience far more nuisance odors than the other six receptors. These results agree with Omaha, Nebraska weather patterns where the predominant winds are along the NW-SE diagonal.

Table 4. Example calculations for building odor emission rates used in model.

Month	**Tave** (C)	**WSave** (m/s)	**VPA** (m^3/hr-pig)	**VB** (m^3/hr)	**$OU_{Building}$**	**Average Odor Emission** (OU/hr)
March	1.7	5.0	26.1	104,400	939	98,031,600
April	10	5.8	69.7	278,800	750	209,100,000
May	16.7	5.8	104.9	419,600	598	250,920,800
June	21.7	4.6	127.5	510,000	500	255,000,000
July	23.9	3.6	127.5	510,000	500	255,000,000
August	22.8	3.8	127.5	510,000	500	255,000,000
September	18.3	4.9	113.3	453,200	561	254,245,200
October	12.2	4.2	81.3	325,200	700	227,640,000

Table 5. Predicted number of hours of exposure to OU=7 or greater.

Receptor	**Distance (m)**	**Direction from Source**	**Hours Subjected to OU=7 or Greater** *Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Total*
1	400	NE	3.0	9.4	3.6	2.3	1.8	2.4	3.3	1.5	27.3
2	400	SE	16.3	35.9	11.5	8.2	7.9	6.7	9.8	14.1	110.4
3	400	SW	5.2	9.4	3.0	3.5	4.8	3.6	3.9	3.7	37.1
4	400	NW	11.1	20.3	10.3	10.0	9.7	12.1	7.8	11.1	92.4
5	800	NE	1.5	2.0	1.8	1.2	0.9	1.2	1.6	0.7	10.9
6	800	SE	8.2	7.5	5.8	4.1	3.9	3.3	4.9	7.0	44.7
7	800	SW	2.6	2.0	1.5	1.8	2.3	1.8	2.0	1.9	15.9
8	800	NW	5.6	4.2	5.2	5.0	4.9	6.1	3.9	5.6	40.5

One of the features of the model is that various odor mitigation strategies can be investigated to determine the level of odor control required to meet a given criteria. For example, assume that a proven building odor mitigation strategy of 80 percent odor reduction is incorporated for the case above. The odor load characteristics in this Acommunity@ become as shown in Table 6.

One of the biggest challenges facing the pig industry today is the relationship between producer and the community. Most all siting criteria used in the US rely on a distance only set-back criteria. With a distance-only requirement, it is possible for a multitude of sources to exist in relative close proximity to receptors with all sources meeting the distance-only criteria. However, this policy can result in an excess of nuisance odors at a receptor. The model developed is intended to evaluate this and many other scenarios on a case-by-case basis to determine existing odor loads in a community and the influence of adding more odor load to an existing situation.

For example, assume that the separation distance requirement for a 4,000-head deep-pit finisher is 560 m in an area close to Omaha, Nebraska. For a receptor, subjected to four of these loads located along the diagonals and at this separation distance, the model would predict the OU=7 or greater hours of exposure as shown in Table 7.

Table 6. Predicted number of hours of exposure to OU=7 or greater with 80 percent source odor reduction.

Receptor	**Distance (m)**	**Direction from Source**	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Total*
1	400	NE	1.5	3.9	3.6	2.3	1.8	2.4	3.3	1.5	20.3
2	400	SE	8.1	15.0	11.5	8.2	7.9	6.7	9.8	14.1	81.1
3	400	SW	2.6	3.9	3.0	3.5	4.8	3.6	3.9	3.7	29.1
4	400	NW	5.6	8.5	10.3	10.0	9.7	12.1	7.8	11.1	74.9
5	800	NE	0.0	1.0	0.9	0.6	0.5	0.6	0.8	0.4	4.7
6	800	SE	0.0	3.8	2.9	2.1	2.0	1.7	2.4	3.5	18.3
7	800	SW	0.0	1.0	0.8	0.9	1.2	0.9	1.0	0.9	6.6
8	800	NW	0.0	2.1	2.6	2.5	2.4	3.0	2.0	2.8	17.4

(The header "**Hours Subjected to OU=7 or Greater**" spans the month and total columns.)

Table 7. Effect of multiple sources on a receptor's odor load (OU=7 or greater).

Source	**Distance from Receptor**	**Direction from Receptor**	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Total*
1	560 m	NE	3.7	2.8	2.2	2.5	3.5	2.6	2.8	2.7	22.8
2	560 m	SE	8.0	6.1	7.4	7.2	7.0	8.7	5.6	8.0	58.0
3	560 m	SW	2.1	2.8	2.6	1.7	1.3	1.7	2.3	1.1	15.7
4	560 m	NW	11.7	10.8	8.3	5.9	5.7	4.8	7.0	10.1	64.3
Total for Receptor											**160.8**

(The header "**Hours of Exposure to OU=7 or Greater**" spans the month and total columns.)

Clearly, the receptor would be subjected to an additive odor load from these four sources with sources 2 and 4 having the biggest impact on this receptor. Siting of facilities must consider the effect of multiple odor loads in a community and have procedures in place to make decisions based on local historical weather patterns, facility size, and odor control technologies implemented.

Using a tool like this model to help site and evaluate production facilities requires an agreed-upon criteria for the hours of exposure to various odor levels. A criteria that combines percent time exposure to detectable odors (OU=2 or greater) and percent time exposure to nuisance odors (OU=7 or greater) might be a consideration.

Comparison with Field Measurements

The model using the parameters given above was used to predict measured downwind odor concentrations. The results presented in Table 8 are a few of the downwind odor measurements collected for comparison with the model. These results are shown to highlight the current successes and failures of the model.

Table 8. Model comparison (Pred.) with field measurements (Meas.) *via* scentometry for two distinct swine finishing systems.

Season	**WS (m/s)**	**Sky Condition**	**Day or Night**	**Distance Downwind (m)**	**Pred.**	**Meas.**
4,000-head Deep-Pit Swine Finisher						
Summer	6.7-9	Cloudy	Day	854	4	7
Fall	4.9-5.8	Clear, Sunny	Day	793	1	0.5
Winter	4.5-6.9	Cloudy	Day	1,524	0	0
Fall	0.9-1.3	Partly Cloudy	Day/Night	152	22	7
Fall	0.9-1.3	Partly Cloudy	Day/Night	869	1	4
8,000-head Swine Finisher with Flush from SS Lagoon						
Spring	3.6-5.4	Clear	Night	305	20	15
Spring	3.6-5.4	Clear	Night	793	4	7
Spring	3.6-5.4	Clear	Night	1,037	3	2
Summer	0.5-1.3	Clear	Day	213	14	7
Summer	0.5-1.3	Clear	Day	335	6	2

The predicted levels are generally higher, with the poorest predictions occurring closer to the source (<213 m). With all data given in Table 8, the predicted versus measured data results in an R^2=0.56. If the two measurements at or below a downwind distance of 213 m are excluded from the data set, R^2 improves to 0.77. Data continues to be collected to provide calibration of the developed model. The important aspect for this modeling approach is to provide consistent trends for various atmospheric stability conditions. For example, based on the limited data given in Table 8, it appears that predictions for downwind distances less than about 250 m and predictions during low wind speed conditions (< 1.5 m/s) will need some work.

CONCLUSIONS

A model was developed and is actively being compared to calibration data to predict the odor load experienced in a community from multiple sources. The model can be used to evaluate site selection for a new facility, evaluate proven odor control technologies on new and existing facilities, and evaluate the potential for expansion of an existing facility in an existing community.

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